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Noninvasive Measurement of Internal Jugular Venous Oxygen Saturation by Photoacoustic Imaging

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ABSTRACT

The metabolic rate and oxygen consumption of the brain is reflected in jugular venous oxygen saturation. In many clinical conditions, such as head trauma, stroke, and low cardiac output states, the brain is at risk for hypoxic-ischemic injury. The current gold standard for monitoring brain oxygenation is invasive and requires jugular vein catheterization under fluoroscopic guidance; and therefore it is rarely used. Photo-acoustic tomography in combination with ultrasound can be used to estimate oxygen saturation of the internal jugular vein in real-time. This noninvasive method will enable earlier detection and prevention of impending hypoxic brain injury. A wavelength-tunable dye laser pumped by a Nd:YAG laser delivers light through an optical fiber bundle, and a modified commercial ultrasound imaging system (Philips iU22) detects both the pulse-echo ultrasound (US) and photoacoustic (PA) signals. A custom-built multichannel data acquisition system renders co-registered ultrasound and photoacoustic images at 5 frames per second. After the jugular vein was localized in healthy volunteers, dual-wavelength PA images were used to calculate the blood hemoglobin oxygen saturation from the internal jugular vein *in vivo*. The preliminary results raise confidence that this emerging technology can be used clinically as an accurate, noninvasive indicator of cerebral oxygenation.

Keywords: Photoacoustic measurement, ultrasonography, oxygen saturation.

1. INTRODUCTION

High metabolic demands and a lack of a well-developed collateral circulation make brain tissue highly susceptible to hypoxic-ischemic injury. In most neurological disease states, a final common pathway, characterized by compromise of cerebral perfusion, oxygenation, and metabolism, results in the permanent brain injury and death. Similarly, brain hypoxia/ischemia can also occur during many complex surgical or diagnostic procedures, e.g. carotid endarterectomy, cardiac surgeries, and neuro-interventional radiological procedures. In particular, patients admitted to critical care units for traumatic brain injury, multi-organ failure, and septicemia, frequently develop cardio-respiratory insufficiency, which frequently leads to brain ischemia [1]. Even with extensive monitoring of hemodynamic parameters like arterial blood pressure, arterial oxygen saturation, and central venous pressure imbalance between oxygen

supply and the metabolic demands of brain tissue can persist and go undetected [2]. Improving oxygen delivery to match the metabolic demands is essential for managing patients where brain tissue is anticipated to be at risk from ischemic injury. To prevent brain ischemia would require a point of care monitor that can consistently detect inadequate global cerebral oxygen perfusion. Currently available bedside monitors have failed to provide a reliable monitor for detecting either brief or prolonged episodes of global brain ischemia. Near infrared spectroscopy (NIRS) is one non-invasive method that is used to monitor oxygen saturation of a composite tissue located under the probe [3]. A major limitation of these monitors is their key assumption about the composition of the cerebral blood (15 -20% arterial, 70-80% venous and 5-10% capillary) in the path of the near infrared light. This assumption may not hold true in many patients, especially in children [4,5].

Monitoring oxygen saturation in the venous blood draining from brain is one reliable way of monitoring adequacy of global brain perfusion that is frequently used in patients with traumatic brain injury. Changes in the global oxygen consumption are closely related to the changes of internal jugular vein (IJV) oxygen saturation (S_{ijvO_2}). Unfortunately, monitoring S_{ijvO_2} requires placing a vascular catheter in the jugular bulb. This procedure thus can be performed only in the operating room or under fluoroscopic guidance. Routine use of S_{ijvO_2} is further limited because of many other challenges, such as the development of micro-thrombi at the tip of the catheter and need for frequent calibration. In addition, one has to predict the dominant side of the venous drainage prior to the placement of the invasive catheter, making routine monitoring of S_{ijvO_2} impractical. Here, we propose a non-invasive monitoring of the internal jugular vein oxygen saturation based on combining photoacoustics and ultrasound. This approach can measure the S_{ijvO_2} in real time without risk to the patient [6,7].

2. PHOTOACOUSTIC AND ULTRASOUND IMAGING SYSTEM

We developed a photoacoustic tomography (PAT) and ultrasound (US) imaging system around a modified clinical US scanner (iU22, Philips Healthcare). A system diagram is shown in Fig. 1. The light sources were a wavelength tunable dye laser (PrecisionScan-P, Sirah, Kaarst, Germany), and Q-switched Nd:YAG laser (QuantaRay PRO-350-10, Spectra-Physics, Santa Clara, CA). The laser pulse was coupled to a fused end, bifurcated fiber bundle that flanked both sides of a linear ultrasound array. The laser emitted pulses at a repetition rate of 10 Hz and pulse duration of 6.5 ns. All per-channel data from the US transducer were transferred to a custom-built data acquisition (DAQ) computer, which performed image reconstruction and display of the PAT images.

The system was designed to operate in two different modes: the first mode acquires and displays PA and US co-registered images (PA/US mode), while the second mode acquires and displays dual wavelength photoacoustic images (dual PA mode). During PA/US mode, the PA and US images were collected alternatively. At the same time, they were processed and overlaid so that we could locate accurately the source of the PA signals with the help of the US images. The co-registered images were displayed at 5 frames/s. For the dual-PA mode, we selected two wavelengths, 782 nm from the dye laser and 1064 nm from the Nd:YAG laser. A mechanical shutter was synchronized to the laser trigger and alternatively blocked either the dye output or

the fundamental output on consecutive laser shots. The two wavelengths were routed to the same path by a dichroic mirror before being coupled to the fiber bundle.

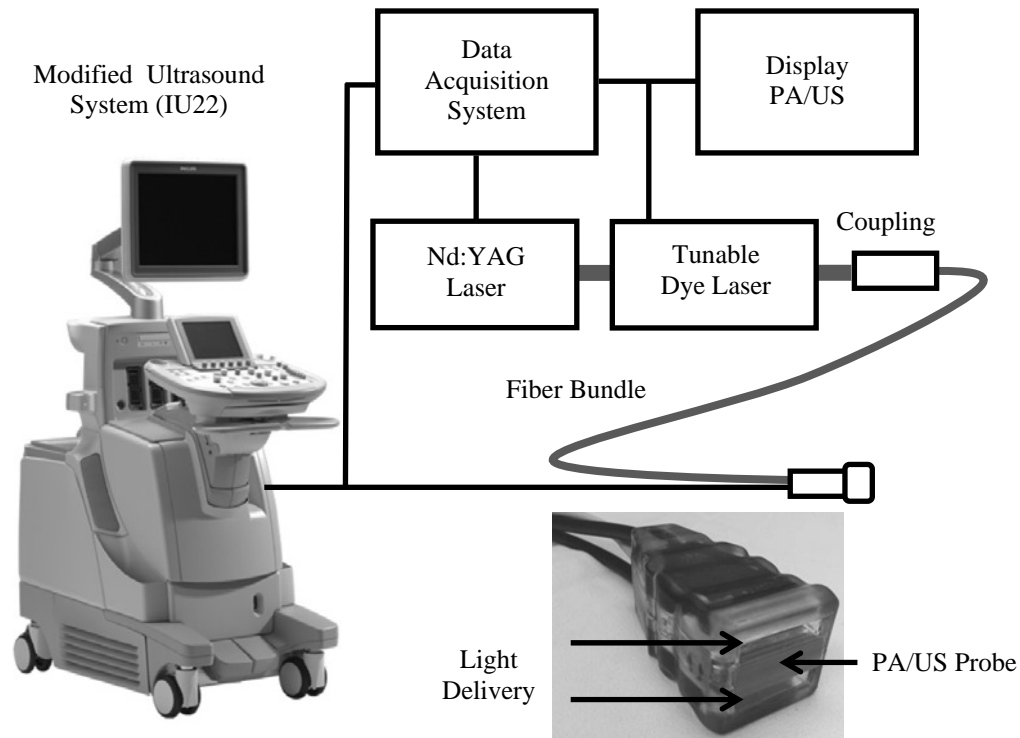


Figure 1. Schematic of the dual-modality photoacoustic and ultrasound imaging system and improved transducer design. The transducer features a flat surface for light delivery and fiber bundles that are integrated into the transducer housing for easier handling.

3. RESULTS

First we collected the PA and ultrasound US image of the cross-section of the IJV. Figure 2 shows the PA, US, and co-registered images acquired from a healthy normal volunteer. The combination of US and PA images allowed us to accurately locate the PA signal from the jugular vein. After localizing the PA signal from the jugular vein, we switched to PA mode and collected PA images generated at two optical wavelengths. Figure 3 shows the PA images for 782 and 1064 nm respectively. The PA signal for the IJV was segmented and averaged. The oxygen saturation was calculated every 2 frames (five times per second). The average oxygen saturation for this case was 67%. The preliminary results are encouraging and are in agreement with those reported in the literature [8]. The results from this study are an important step toward clinical translation of photoacoustic imaging into a noninvasive tool for monitoring $SjvO_2$ to prevent brain hypoxic-ischemic injuries.

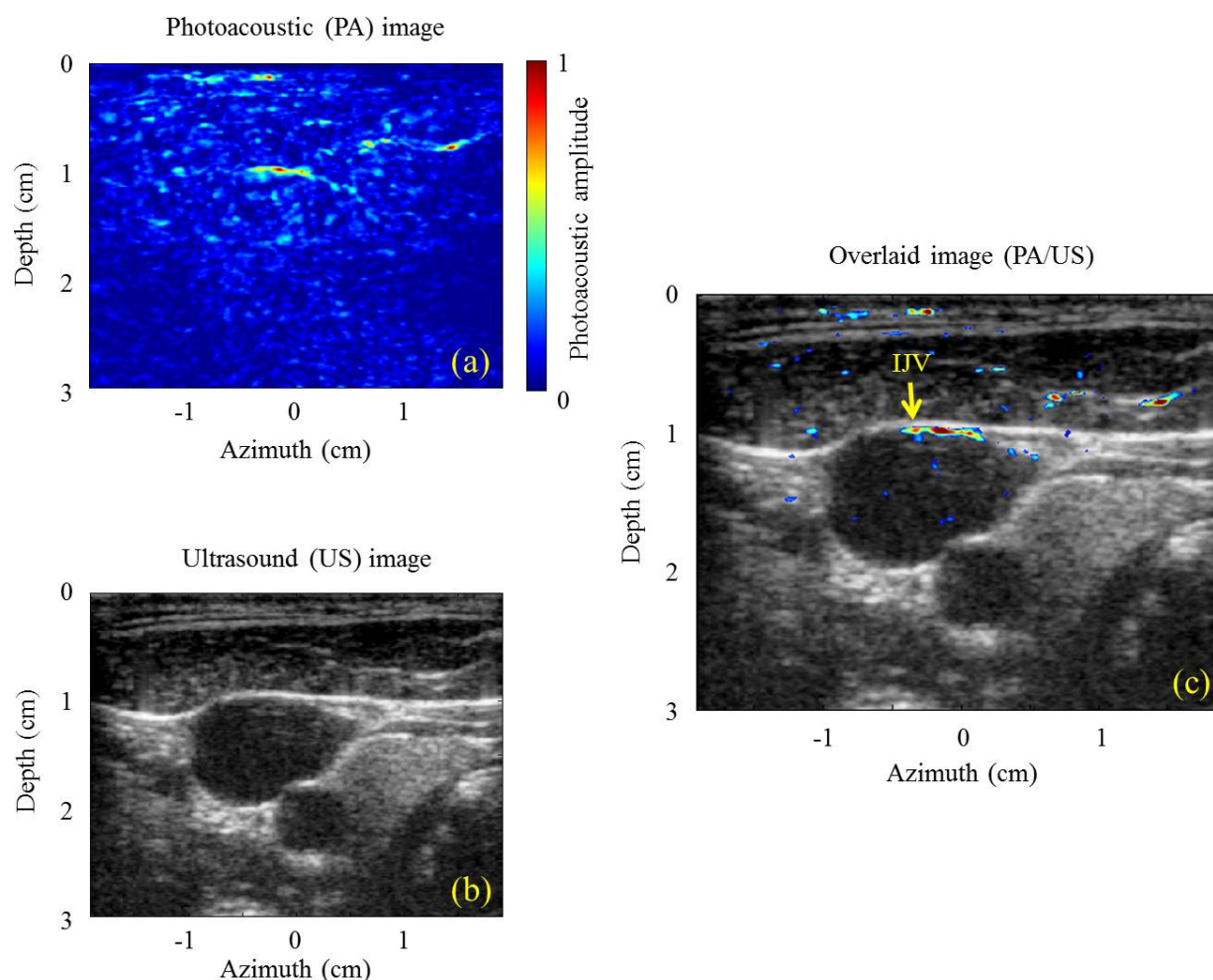


Figure 2. *In vivo* images of the internal jugular vein (IJV) acquired using PAT-US. (a) *In vivo* PA image (b) *In vivo* US image. (c) Overlaid PAT-US image of the IJV.

4. CONCLUSIONS

We successfully developed a dual-wavelength photoacoustic and integrated ultrasound system capable of real time noninvasive measurement of oxygen saturation in the internal jugular vein. These preliminary results raise confidence that this emerging technology can be used clinically for accurate monitoring of $SjvO_2$. We expect that changes in the global oxygen consumption of the brain can be mirrored closely to changes of $SijvO_2$. In addition the fast co-registration of PA and US images makes the technique suitable for studying the temporal variations of oxygen saturation in response to physiologic challenges in clinical settings.

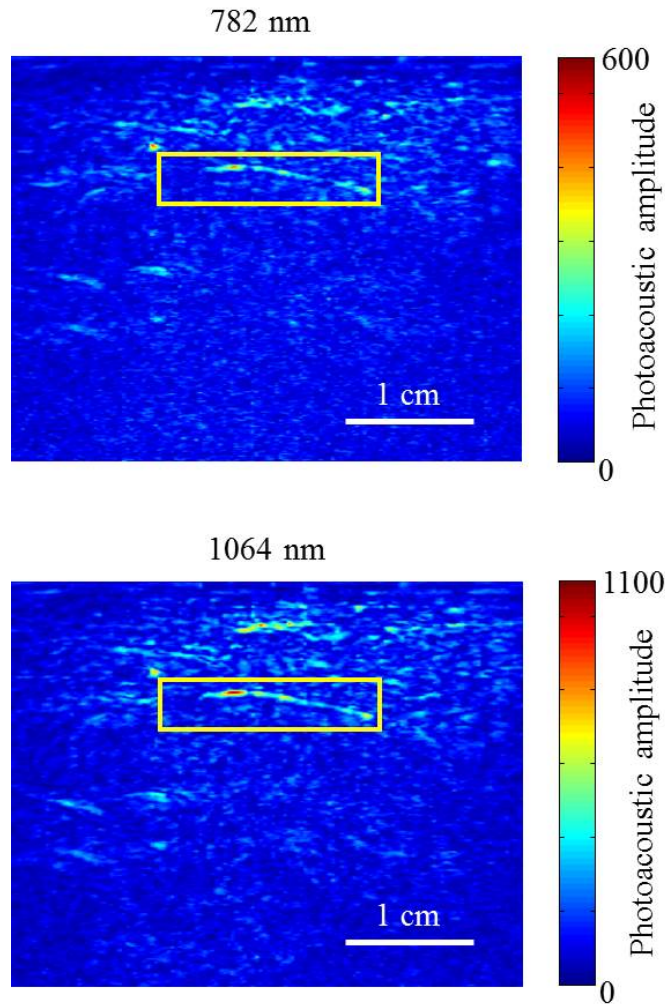


Figure 3. *In vivo* dual wavelength photoacoustic images of the internal jugular (a) *In vivo* PA image at 782 nm (b) *In vivo* PA image at 1064nm.

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